

COSMO-2002

Chicago, 18-21 Sep.

ACTIVE NEUTRINOS in COSMOLOGY.

Neutrino is the second most abundant particle in the universe, after γ of CMBR

$$\frac{n_{\nu_a} + n_{\bar{\nu}_a} \approx 110 \text{ /cm}^3}{a = e, \mu, \tau \Rightarrow 336 \text{ /cm}^3} \quad (n_\gamma \approx 410 \text{ /cm}^3) \quad T_\gamma = 2.725 \text{ K}$$

Spectrum:

$$f_\nu = \frac{1}{e^{p/T - \frac{1}{2}} - 1}, \quad f_{\bar{\nu}} = \frac{1}{e^{p/T - \frac{1}{2}} - 1}$$

$$p = (E^2 - m^2)^{1/2} \neq E \text{ if } m \neq 0$$

$\overline{\beta} = -\beta$ possibly but not necessarily;
most probably $\beta \sim \overline{\beta} \sim 10^{-9}$

$$T_\nu = 1.95 \text{ K}$$

CMBR: witness of $z=10^3$, $t_u \sim 10^5$ y

CBR: witness of $z=10^{10}$, $t_u \sim 1 \text{ sec}$

cosmic neutrino
background radiation

Can we make cosmic v's talking?

and study the early universe history
or vice versa

study neutrino properties
(or both)

I. Direct observations of CBR -
- probably not tomorrow

II. Indirect:

1. LSS (large scale structure)

2. CMBR (cosmic microwave background radiation)

3. BBN (big bang nucleosynthesis)

4. UHECR (ultra high energy cosmic rays)

Essential quantities:

Ch3

Masses

Spectra and, in particular, $\bar{\nu}$

Non-standard interactions

(magnetic moments, right-handed currents, coupling to light scalars)

Possible instability and decay modes

Laboratory data:

$$m(\nu_e) < 3 \text{ eV}, \quad m(\nu_\mu) < 190 \text{ keV}$$

$$m(\nu_\tau) < 18 \text{ MeV}$$

Mixing: $\nu_\mu \leftrightarrow \nu_\tau$ $\delta m^2 = (2-5) \cdot 10^{-3} \text{ eV}^2$
atmospheric $\sin^2 \theta = 0.3 - 0.7$

$$\nu_e \leftrightarrow \nu_a$$

solar

most favored LMA:

$$\delta m^2 \sim 6 \cdot 10^{-5} \text{ eV}^2, \quad \tan^2 \theta = 0.4$$

Disfavored

L OW: $\delta m^2 \sim 10^{-7} \text{ eV}^2, \quad \tan^2 \theta = 0.9$

SMA: $\delta m^2 \sim 5 \cdot 10^{-6} \text{ eV}^2, \quad \tan^2 \theta \sim 5 \cdot 10^{-4}$

VAC: $\delta m^2 \sim 5 \cdot 10^{-10} \text{ eV}^2, \quad \tan^2 \theta \sim 2$

50% admixture of sterile ν is not excluded

Early history of neutrinos

Ch 4

Thermal equilibrium at high T .

Decoupling from e^+, e^-, γ at

$T = 1.9 \text{ MeV}$ for ν_e

$T = 3.1 \text{ MeV}$ for $\nu_{\mu, \tau}$

Cosmological expansion does not
destroy equilibrium spectrum of
massless particles

but: at $T \sim m_e$ $e^+e^- \rightarrow 2\gamma$
heats photons

$$\text{initial } \frac{n_\nu + n_{\bar{\nu}}}{n_\gamma} = \frac{3}{4} \rightarrow \underline{\frac{3}{11}}$$

Moreover, decoupling is not instantaneous
and $e^+e^- \rightarrow \nu\bar{\nu}$ and distort ν -spectrum

$$\frac{\delta f_{\nu_e}}{f_{\nu_e}} = 3 \cdot 10^{-4} \frac{E}{T} \left(\frac{11}{4} \frac{E}{T} - 3 \right)$$

$$\delta \rho_{\nu_e} = 0.9\%, \quad \delta \rho_{\nu_{\mu, \tau}} = 0.4\%$$

Together with plasma corrections (Chicago)
 $\delta \rho = 4\%$

$$\Delta \rho_v = 4\% \Rightarrow \underline{\Delta {}^4 \text{He} \sim 10^{-4}}$$

(because total rise of ρ_v is compensated by opposite sign effect from spectrum distortion of ν_e)

However it may be observable in CMBR (Planck, with 1% accuracy and known cosmological parameters)

$$\Omega_{\text{rel}} = \Omega_\gamma [1 + 0.68 \cdot \frac{N_\nu}{3} \left(\frac{1.401 T_\nu}{T_\gamma} \right)^4]$$

$$N_\nu = 3 \rightarrow \underline{N_\nu = 3.04}$$

[effect not calculated for $m_\nu \neq 0$;
 $T_\nu^{\text{now}} = 1.5 \cdot 10^4 \text{ eV} \otimes z_{\text{rec}} = 10^3 \Rightarrow \underline{0.15 \text{ eV} \leftrightarrow m_\nu}$?]

$$\underline{\text{Today}} \quad n_{\nu_\alpha} + n_{\bar{\nu}_\alpha} = 112 / \text{cm}^3$$

$$\rho_\nu = \sum_a m_a \cdot 112 / \text{cm}^3 \quad \leftrightarrow \quad \rho_c = 10.5 h^2 \frac{\text{keV}}{\text{cm}^3}$$

$$h = \frac{H}{100 \text{ km/sec/Mpc}}$$

$$\Omega_\nu = \rho_\nu / \rho_c < \Omega_{\text{matter}}$$

$$\sum_a m_a < 94 \text{ eV } h^2 (\Omega_\nu / \Omega_m) \Omega_m$$

Gerstein-Zeldovich Bound

$$h^2 \approx 0.5, \quad \Omega_m \approx 0.3, \quad \Omega_\nu / \Omega_m < \frac{1}{3} (?)$$

from LSS

$$\sum m_{\nu_\alpha} < 4.7 \text{ eV} \quad \text{and if } m_{\nu_e} \approx m_{\nu_\mu} \approx m_{\nu_\tau}$$

$$m_{\nu_\alpha} < 1.6 \text{ eV}$$

Why LSS demands $\Omega_\nu / \Omega_m < \frac{1}{3}$?

Neutrino free streaming

Neutrinos are very relativistic at decoupling and move with speed of light till $T_\nu \approx m_\nu / 3$

$$l_{\text{free stream}} \approx 2t (T_\nu = m_\nu / 3)$$

$$M_{\text{free stream}} \approx 0.1 \frac{m_{\text{pe}}^3}{m_\nu^2} \approx 5 \cdot 10^{12} M_\odot \left(\frac{1 \text{ eV}}{m_\nu} \right)^2$$

If density perturbations are common for all particles (e.g. adiabatic ones created by inflation) neutrino out-stream would leave behind less power at small scales.

1. The larger $S_{\nu_\text{}} \text{, the stronger effect.}$
2. The larger fraction of relativistic matter (hot matter), the later structure formation begins.

Observations of structures at high z (will) permit to obtain $\sum m_\nu < 2-3 \text{ eV}$?

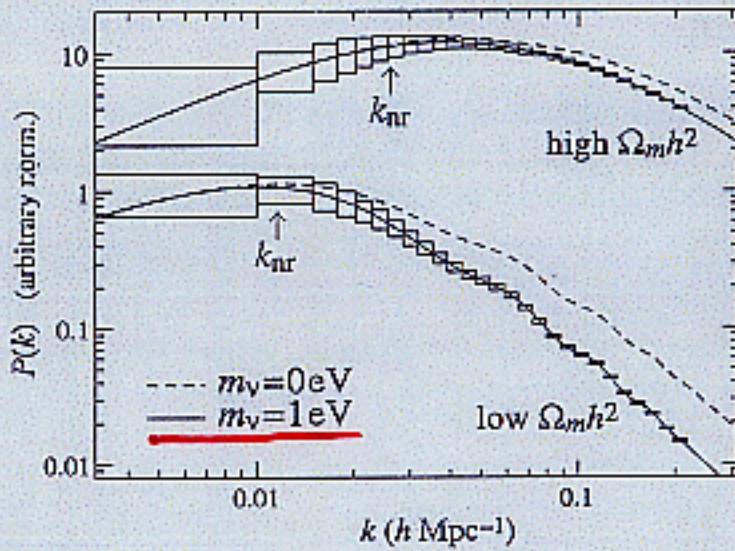


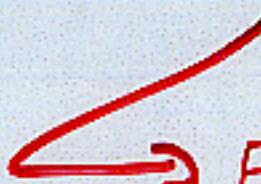
Figure 21: Effect of a 1 eV neutrino on the bright red galaxy (BRG) power spectrum compared with expected precision of the SDSS BRG survey (1σ error boxes). Upper curves: an $\Omega_m = 1.0$, $h = 0.5$, $\Omega_bh^2 = 0.0125$, $n = 1$ model with and without a 1 eV neutrino mass. Lower curves: the same but for an $\Omega_m = 0.2$, $h = 0.65$ model.

(from Hu et al, astro-ph 9806352)

Sloan Digital Sky Survey (SDSS)
may be sensitive to $m_\nu \sim 0.1$ eV
(if all other cosmological
parameters are known)

Is it still possible that neutrinos make all dark matter in the universe allowing any spectrum of primordial perturbations and arbitrary new interactions of neutrinos?

No! Forbidden by Tremaine-Gunn limit.

 Fermi exclusion principle at 1 kpc scale.

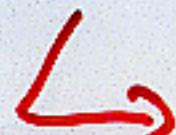
Degenerate ν -gas (with $\bar{\chi}_\nu = \bar{\chi}_{\bar{\nu}}$)

and Fermi momentum : $p_F = m_\nu V_F$

$$n_\nu + \bar{n}_\nu = \frac{2p_F^3}{6\pi^2}, \quad M_{\text{total}} = \frac{4}{3}\pi R_{\text{gal}}^3 \frac{p_F^3}{3\pi^2} \cdot m_\nu$$

Virial theorem : $V_F^2 = G_N M_{\text{gal}} / R_{\text{gal}}$

$$M_\nu = 80 \text{ eV} \left(\frac{300 \text{ km/sec}}{V_F} \right)^{1/4} \left(\frac{1 \text{ kpc}}{R} \right)^{1/2}$$

 $m_\nu > 100 \text{ eV}$ (contradicts GZ)

Back to beginning ...

BBN

$$t = 0.1 \rightarrow 300 \text{ sec}$$

$$T = 3 \text{ MeV} \rightarrow 65 \text{ keV}$$

Energy density:

$$\rho = \frac{3H^2}{8\pi} m_p c^2 = \frac{3m_p^2}{32\pi t^2} = \frac{\pi^2}{30} g_* T^4$$

$$g_* = 10.75 + \frac{7}{4}(N_s - 3)$$

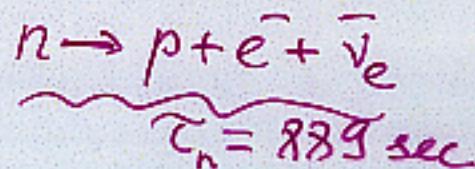
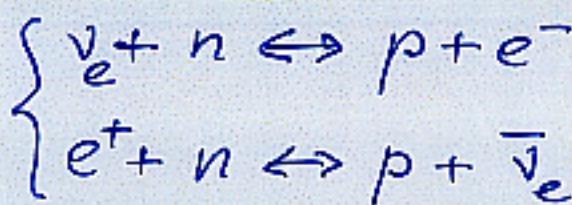
$\gamma, e^+, e^-, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

standard parametrization
of any non-standard
form of energy

Cooling rate: $t(T) \sim \underline{g_*^{-1/2} T^{-2}}$

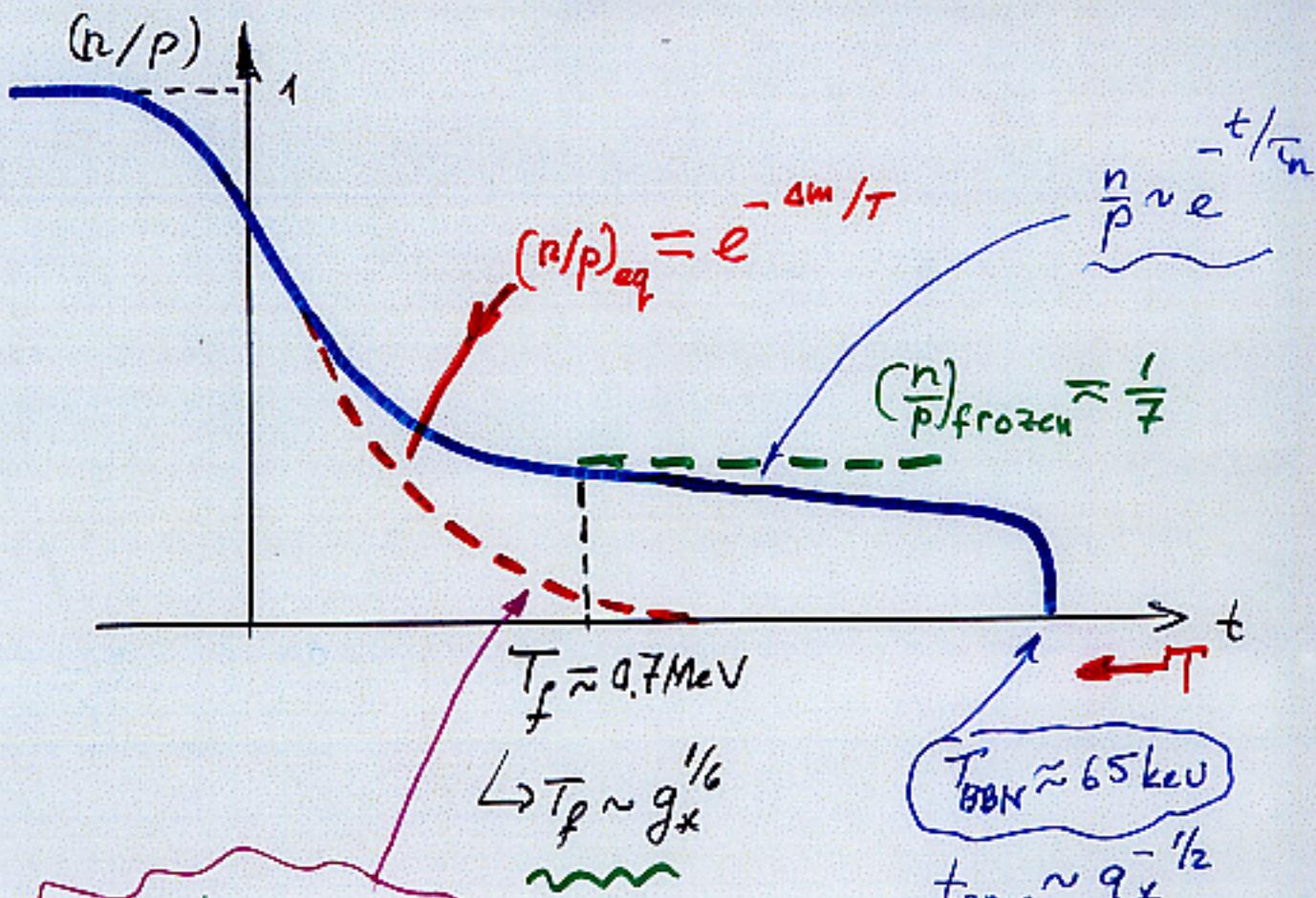
depends on all forms
of energy.

Preparation of building blocks:



$$(n/p)_{eq} = e^{-\Delta m/T - \frac{3}{2}\nu_e}$$

$$\Delta m = m_n - m_p = 1.3 \text{ MeV}$$



If ^{neutrino} weak interactions were a little weaker no neutrons would remain and no ⁴He formed

$T_{BBN} \approx 65 \text{ keV}$
 $t_{BBN} \approx g_*^{-1/2}$
 $\approx 3 \cdot 10^{-5} \text{ g}$
 $\approx 25\% \text{ } ^4\text{He}$
 $\approx 3 \cdot 10^{-10} \text{ } ^7\text{Li}$

Role of neutrinos in BBN

C611

I. contribution into total energy density and cooling rate coefficient

g_A

$$\Delta N_\nu = N_\nu - 3$$

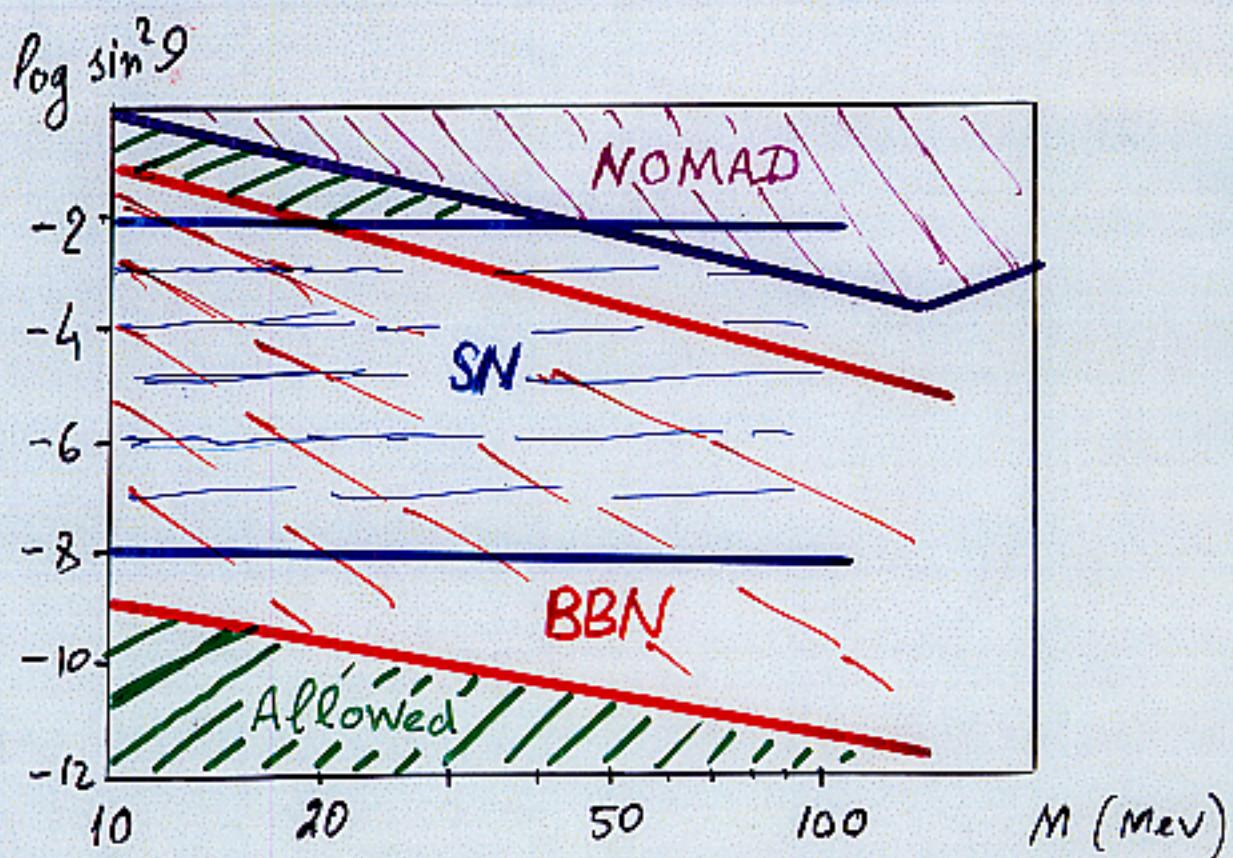
$$\text{if } \underline{\Delta N_\nu = 1} \quad \underline{\Delta \text{He}^4 \approx 5\%}$$

Observational limits:

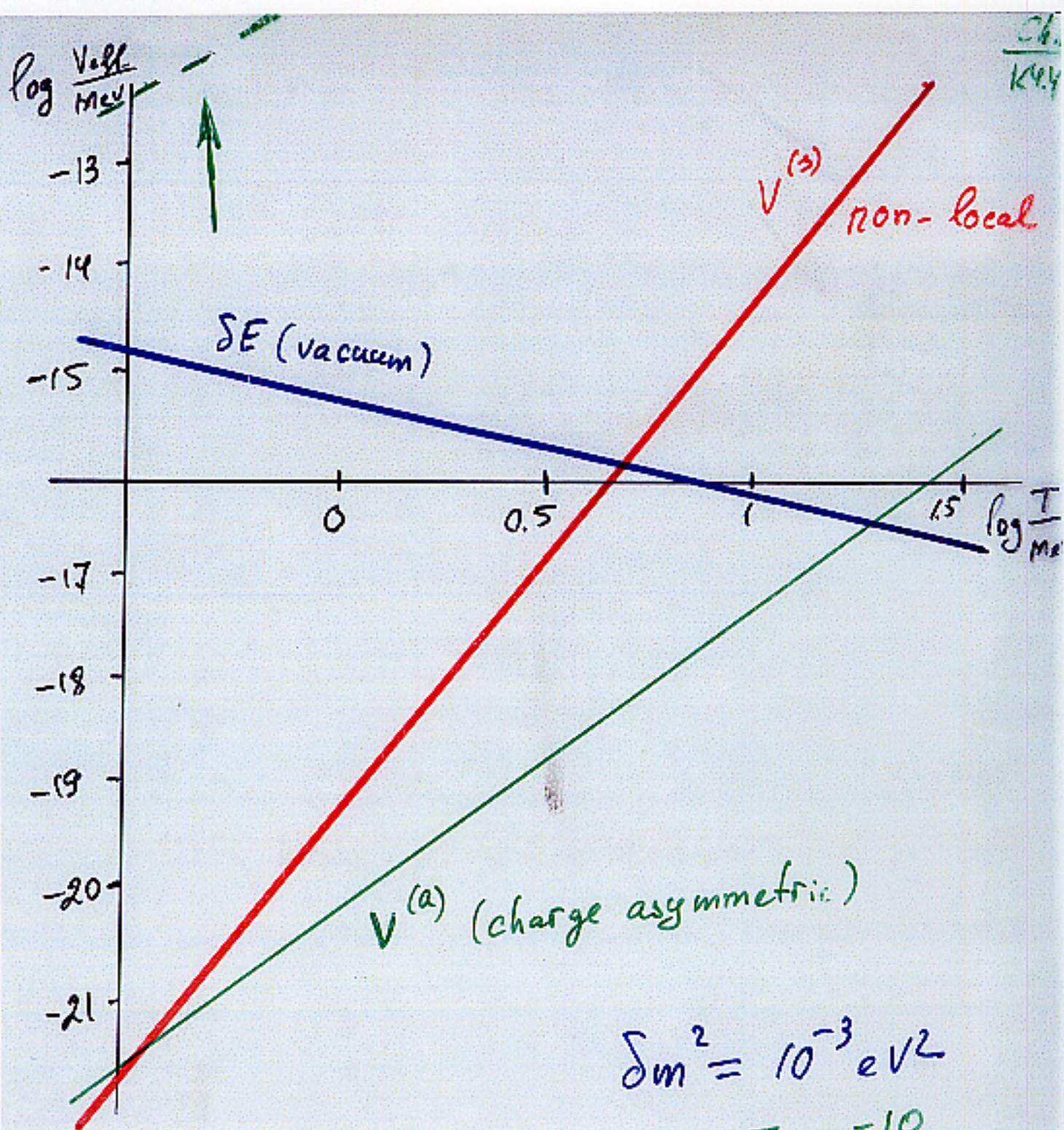
optimistic: $\Delta N_\nu < 0.2$

pessimistic: $\Delta N_\nu < 1$

Heavy ν , mixed with active ones



All above mentioned effects are important: change of N_e ,
 drop of ν_e/γ ,
 distortion of ν_e spectrum
 change $T(t)$ because of annihilation



$$\delta m^2 = 10^{-3} \text{ eV}^2$$

$$\eta = 5 \cdot 10^{-10}$$

$$\left\{ \begin{array}{l} \delta E \approx 5 \cdot 10^{-13} \frac{\delta m^2 / \text{eV}^2}{E / \text{MeV}}, \\ V^{(g)} \approx 5 \cdot 10^{-20} T^5 (E / \beta T) \\ V^{(a)} = \pm 10^{-21} \left(\frac{2}{10^{-10}}\right) T^3 \end{array} \right\}$$

All in MeV

Possible effects of ν -oscillations on BBN

Ch 17

1. Change of ρ_0 ($\Delta N \neq 0$)
2. Distortion of ν_e spectrum
3. Creation or destruction of lepton asymmetries

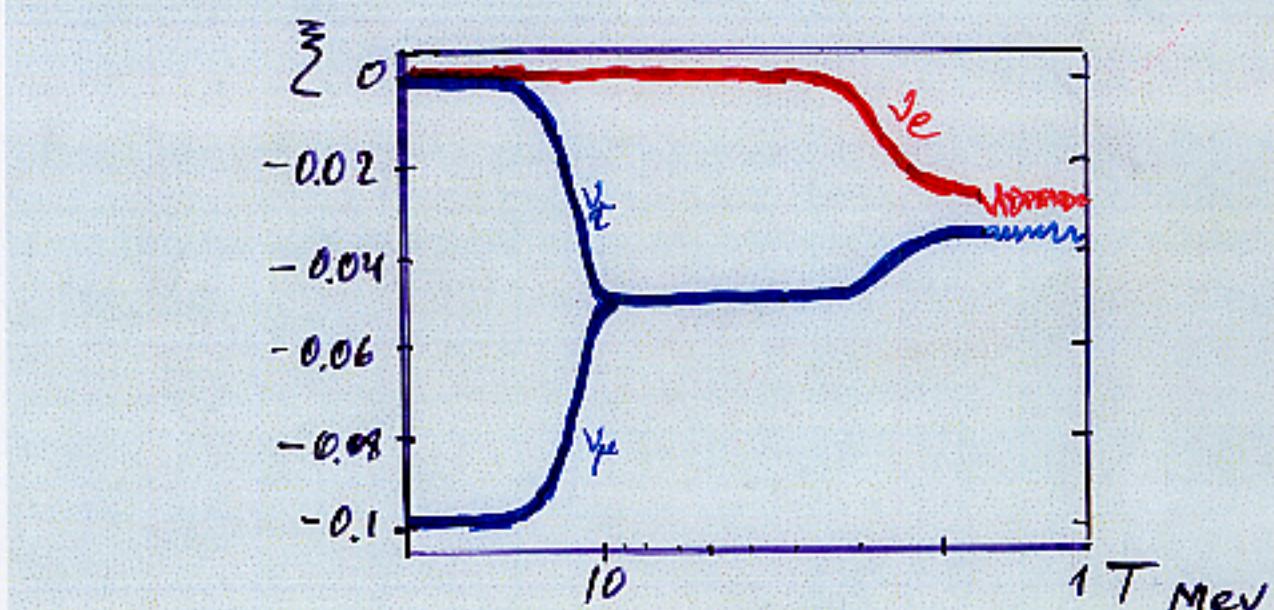
If initially neutrinos were in equilibrium, no new effects.

Deviation from equilibrium:

- A. By hotter $e^+e^- \rightarrow \bar{\nu}\bar{\nu}$, still remains $\Delta \text{He}^4 \sim 10^{-4}$ even if $\nu_e \leftrightarrow \nu_\mu$

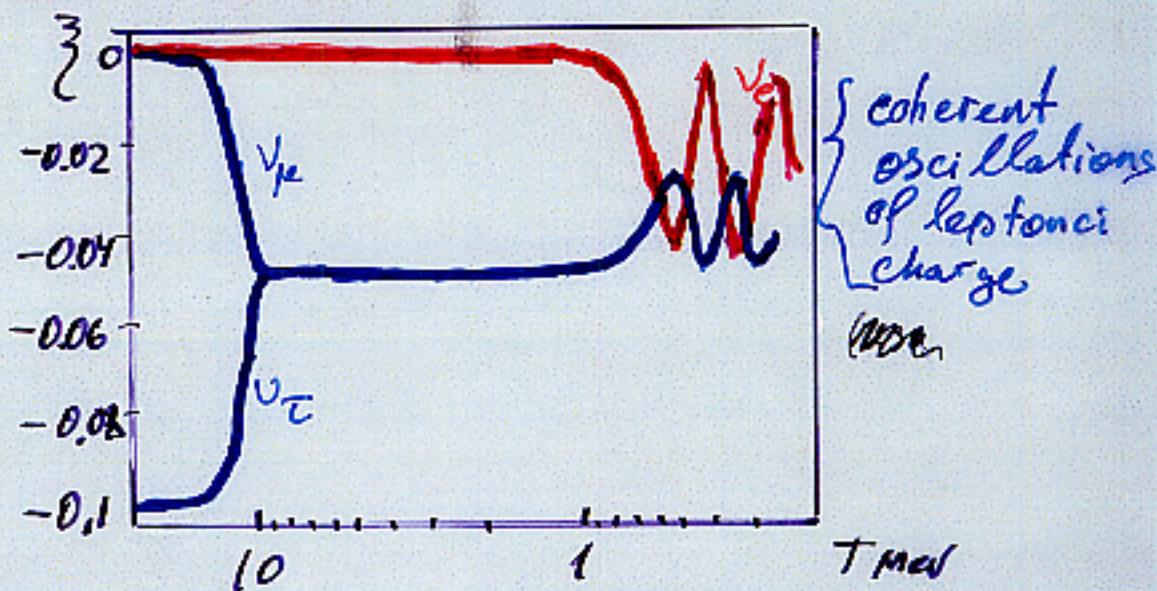
$$\nu_e \leftrightarrow \nu_\mu$$
$$\nu_e \leftrightarrow \nu_\tau$$

Oscillations could change spectrum and destroy compensation - but they don't.



LMA solution $\tan^2 \theta = 0.41$, $\delta m^2 = 4.5 \cdot 10^{-3}$ eV^2

$|\beta_{\text{val}}| < 0.07 \leftarrow \text{from BBN}$



LOW solution $\tan^2 \theta = 0.71$

$$\delta m^2 = 10^{-7} \text{ eV}^2$$

Hansen
Paschos, Petrou, Raffelt
Somikos
AS

Nicole Bell

Generation of large lepton asymmetry by ν -oscillations.

75
K4.1

Assumptions: only one \Rightarrow

existence of sterile neutrino, ν_s ,
mixed with any active one

with $\theta < 10^{-2}$, $|\delta m^2| > 10^{-2} \text{ eV}^2$

Resonance oscillations create
lepton asymmetry in active ν sector
 $L = (n_\nu - n_{\bar{\nu}}) / (n_\nu + n_{\bar{\nu}}) \sim 1 \quad (0.3 - 0.4)$ 375
max

If these are small in homogeneity
in e.g. baryon asymmetry $\delta B/B \sim 10^{-5}$
(with $B \sim 10^{-9} - 10^{-10}$) then
 $(\delta L/L) \sim 1$ would be generated.

Spatial variation.

(P. di Bari)

115
K4.10

$$\frac{L}{v_k} = \alpha(\tilde{\tau}) [2L_{va} + L + \delta B(x)] + \beta(\tilde{\tau}) \nabla^2 L_{va}$$



$$\alpha(t) = \alpha(t - t_c)$$

$$L_{va} = \int_{t_{in}}^T \alpha(t') e^{2 \int_{t'}^T \alpha(t'')} dt'' + (\sim L_{in})$$

$$+ \int_{t_{in}}^T \alpha(t') e^{2 \int_{t'}^T \alpha(t'')} \int dk e^{ikx} \delta \tilde{B}(k, t_{in})$$

$$\Rightarrow e^{2 \int_{t_{in}}^T \alpha(t'')} \left[\int \delta^{(3)}(k) + \frac{1}{2} B_k e^{-k^2 \int_{t_{in}}^T \alpha(t'')} \right]$$

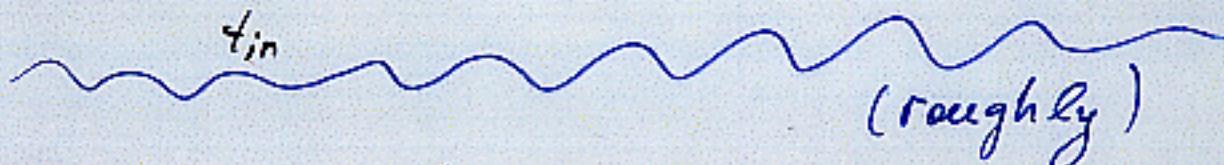
K-modes contribute both $\alpha > 0$ and $\alpha < 0$

$$+ \frac{1}{2} \delta B_k k^2 \int_{t_{in}}^T dt' e^{t' \int_{t'}^T \alpha(t'')} e^{-k^2 \int_{t_{in}}^T \alpha(t'')} \delta(t'')$$

is not strongly suppressed for negative $\alpha(t'')$

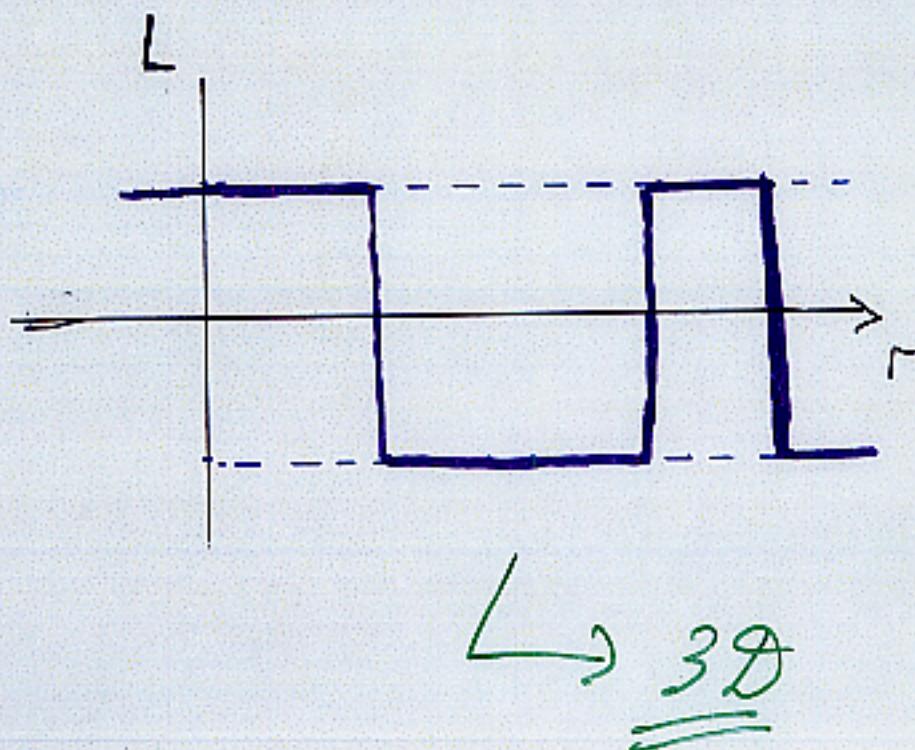
Integral is dominated by t'' where $\alpha(t'') > 0$. Exponential rise for large T is the same.

In a range of k , $k_{\min} < k < k_{\max}$
such that

$$\delta B k^2 \int_{t_{in}}^{\tau} dt' \delta(t') e^{-k^2 \int_{t'}^{\tau} \delta(t'') dt''} > L_{\min}$$


the sign of L_{as} is determined
by the sign of δB

($B \sim 5 \cdot 10^{-10}$, $\delta B / B < 10^{-3}$ from CMBR
"normal" $\delta B / B \sim 10^{-5}$?)



Conclusions

1. Astronomy opens the best way to measure m_ν ; accuracy $\sim 1 \text{ eV}$
2. Physics of ($T = 1 \text{ MeV}$, $t = 1 \text{ sec}$) - universe may be tested by CMBR
3. Less freedom in non-standard BBN because of strong $\nu_e - \nu_\mu$ mixing
 $\nu_e - \nu'_e$ mixing
(if LMA is realized)
4. If ν_S exists with $10^{-5} < \sin\theta < 10^{-2}$ and $\delta m^2 = m_S^2 - m_a^2 < 0$, and $\delta m^2 \sim 1 \text{ eV}^2 - 10 \text{ eV}^2$ then $L_a \rightarrow 0.3 \text{ (0.1)}$
and large $\Delta L(x)$ may be expected
 \hookrightarrow GW and seed magnetic fields